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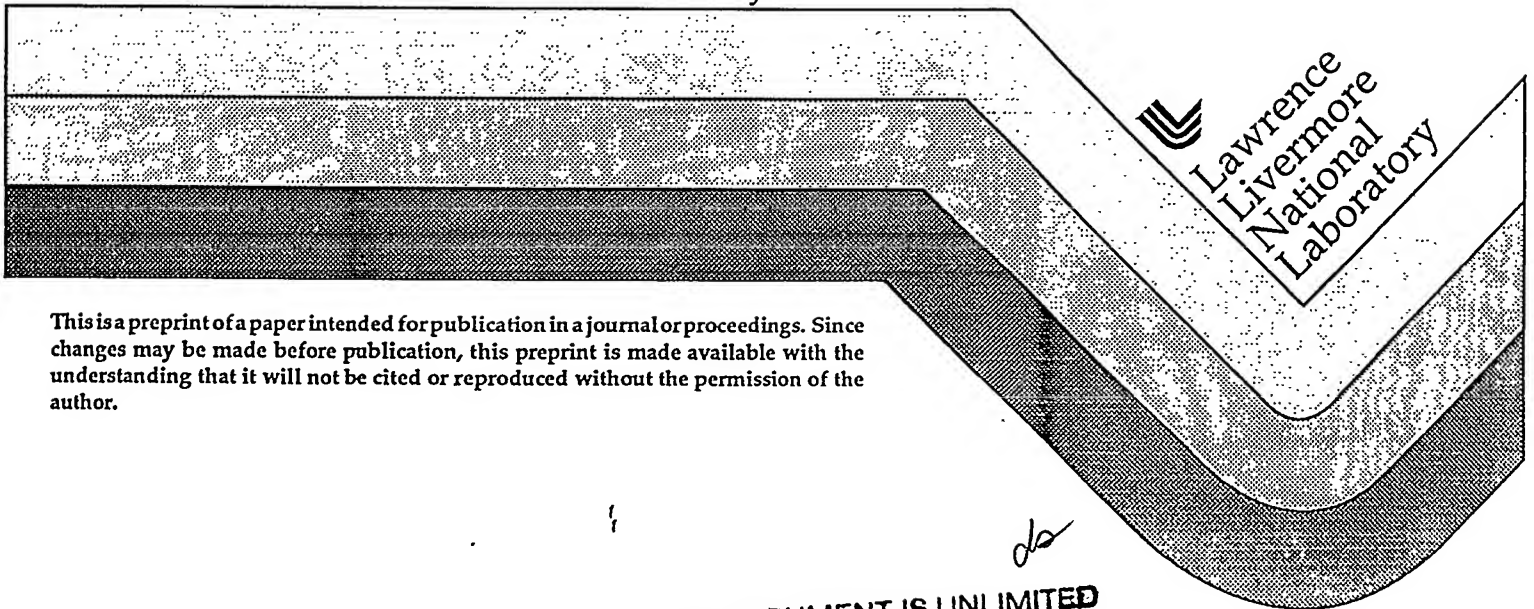
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EXAMINATION OF SHAPED CHARGE LINER SHOCK LOADING*

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A series of experiments was conducted for the purpose of achieving a more fundamental understanding of the shaped charge liner shock loading environment. The test configuration, representing the middle portion of a shaped charge, consists of a 50 mm deep, 100 mm tall, and 2 mm thick copper plate driven by 50 mm deep, 100 mm tall, tapered thickness wedge of LX-14. An electrically driven 50 mm square flyer is used to surface initiate the base of the LX-14 causing a plane detonation wave to propagate into the explosive wedge along the liner surface. Fabry-Perot laser velocimetry measures the particle velocity time history of the plate. The CTH and DYNA2D hydrocodes are used to simulate the experiments. Calculations of the velocity profiles are compared to the experimental results. The effects of mesh density, copper material failure and strength models, and explosive detonation models are discussed.

INTRODUCTION

Hydrocodes are effective tools for predicting shaped-charge liner collapse parameters and the resulting jet characteristics. When using them, it is useful to understand the analysis results in the context of the error introduced by less than optimal zoning and other factors. Shaped charge simulations for a typical charge can require hundreds of thousands of computational zones in order to resolve the liner with 4 to 5 zones through the thickness. Time constraints do not allow for detailed investigations of zoning, failure and strength modeling, artificial viscosity, explosive burn, or equation of state effects. In this light, a geometrically simple test configuration was developed to provide high-fidelity diagnostic data in a less rigorous modeling problem. The experimental results have allowed for the investigation of the accuracy of existing modeling techniques, required mesh density, failure, strength, and other effects, as well as the verification of velocity profiles, momentum transfer, and shock levels.

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EXPERIMENTAL CONFIGURATION

The simple test configuration is a planar section (modeled in plane strain) representing the middle portion of an axisymmetric conical shaped charge as shown in Figure 1a. The actual test geometry, shown in Figure 1b, consists of a 50 mm deep, 100 mm tall, and 2 mm thick copper plate driven by 50 mm deep, 100 mm tall, tapered thickness wedge of LX-14. This planar wedge test configuration represents a section of the shaped charge. A complete axisymmetric conical shaped charge was also tested in a companion study [1].

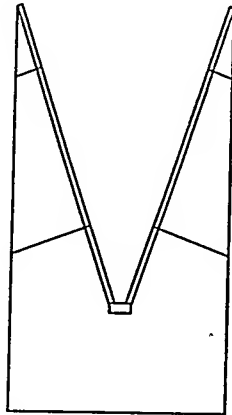


Fig. 1a. Description of axisymmetric conical shaped charge showing middle portion used for planar wedge test.

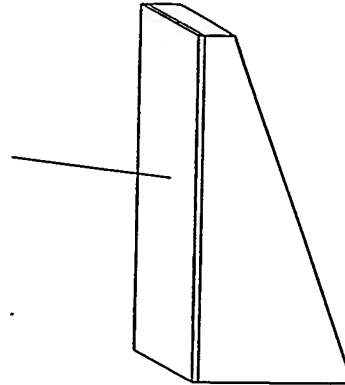


Fig. 1b. Planar wedge test configuration that represents a section of shaped charge. FP laser beam line of sight is at 7 degrees.

An electrically driven flyer initiates the bottom of the LX-14 causing a plane detonation wave to propagate into the explosive wedge along the liner surface. Fabry-Perot (FP) laser velocimetry [2,3] measures the plate velocity time history (in the direction of the laser beam) at a point 67 mm from the bottom. The laser angle is set at seven degrees off the normal from the liner. Edge effects are not a problem since we are only interested in the first few μsec of the liner motion.

HYDROCODE SIMULATIONS

The CTH [4] Eulerian and the DYNA2D [5] Lagrangian wave propagation codes were used to simulate the planar experimental geometry. The equation of state (EOS) option used in CTH for copper was a SNL-SESAME [6] tabular representation of the EOS surface. A standard Grüneisen EOS model was used in DYNA2D with LASL [7,8] published Hugoniot data for copper. The flow stress for the copper was modeled in both codes using the rate-independent version of the Steinberg-Guinan viscoplastic model [9]. The Johnson-Cook [10] and Zerilli-Armstrong [11] copper deviatoric models were also studied using parameter values defined in a previous study [12]. The 370A JWL EOS parameters of Lee [13] were used for the LX-14. Both codes used a pmin material fracture model to treat spallation and both codes were run in plane strain mode.

EXPERIMENTAL RESULTS

The first 1.5 μsec of the FP measured plate velocity time history is shown as a dashed line in Figure 2. The abscissa in the plot is time (μsec) and the ordinate is the FP measured plate velocity ($\text{mm}/\mu\text{sec}$). This curve shows the free surface particle velocity from the first and second HE driven shock reverberations through the copper plate. The initial jump off velocity is about $1.0 \text{ mm}/\mu\text{sec}$ and the reverberation time through the liner is about $0.75 \mu\text{sec}$. Note that the rise time of the first shock pulse is not resolved in the experiment; the plot starts at the peak velocity of the first shock through the plate.

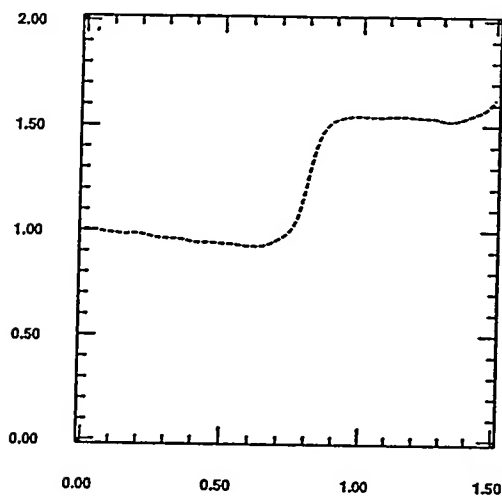


Fig. 2. FP measured plate velocity of the 1st and 2nd HE driven shock reverberations.

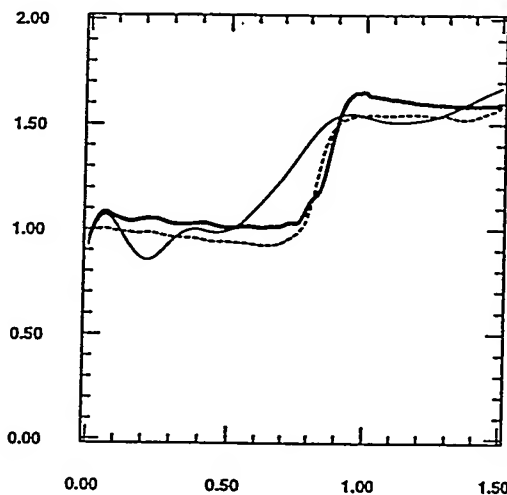


Fig. 3. DYN2D results with p_{\min} set at -0.012 and -9.0 Mbar (spall suppressed).

A comparison of the experimental result to the initial DYN2D calculated results is shown in Figure 3. These calculations were run with 20 elements through the plate thickness by 200 elements along the liner and 40 by 100 elements in the HE. The solid lines in the plot are for results of the analysis with a p_{\min} of -0.012 Mbar and a p_{\min} of -9.0 Mbar (spall suppressed). This zoning density is sufficient for matching momentum transfer in cylinder tests. The -9.0 Mbar p_{\min} (spall suppressed) curve, shown as a light solid line, exhibits more pull back and does not at all look like the experimental result due to its sinusoidal shape. The -0.012 Mbar p_{\min} curve, shown as a dark solid line, more closely matches the shape of the experimental curve (except for the approximately 5% higher velocity). The similarity in shape of the -0.012 Mbar p_{\min} curve with the experimental results would indicate the likelihood of spall (fracture or damage) in the plate.

One possible conclusion is that in order to match the experimental velocity profile, we need to use a p_{\min} of about -0.012 Mbar and let the plate material fail. This is not unreasonable since a p_{\min} value of -0.012 Mbar for half hard OFHC copper is defined by Steinberg [7]. Additionally, some microstructural damage is expected, as a calculated tensile pressure of greater than 0.030 Mbar is observed in the simulation with spall suppressed. However, mesh density, failure modeling, strength modeling, and artificial viscosity modeling studies provide additional insight.

MESH DENSITY STUDIES

Several mesh density studies were conducted to determine the resolution required to accurately compute the measured plate velocity profile. Numerical simulations began by using cell sizes comparable to those used in "typical" warhead calculations (up to 10 elements through the liner) where the primary issue is to have sufficient zoning to accurately treat momentum transfer. This mesh density was found to be inadequate for modeling the velocity profile and shock loading of the copper plate.

The plate motion at late times is primarily a function of momentum transfer, which depends upon the thickness of the explosive and the detonation products at large expansion and as well as the thickness and density of the plate (i.e. charge to mass ratio). The character of the calculated plate motion at early times is determined primarily by the detonation front, including the reaction zone, and the plate thickness. Very fine zoning is required to correctly model the early time plate velocity history.

The mesh density studies summarized below were run with a p_{min} value of -9.0 Mbar (spall suppressed). We found that increasing the density of the mesh along the liner substantially altered the calculated velocity wave profile of the first shock reverberation through the plate. Figure 4 shows the calculated plate velocity using the 200, 400, 600, 800, & 1000 elements along the plate with a constant 40 elements through the plate thickness. The explosive mesh was held constant at 40 by 400 elements.

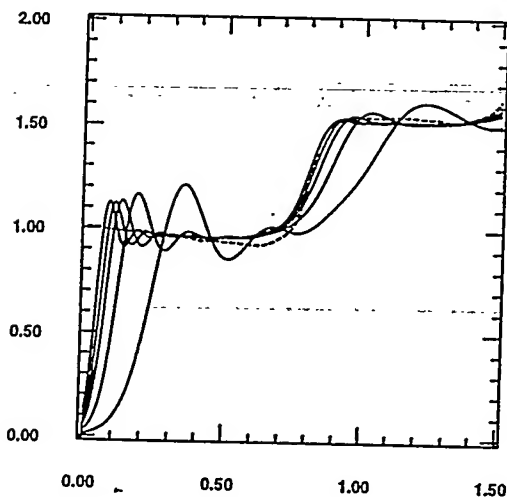


Fig. 4. Mesh Density plots: 200 to 1000 by 40 in liner and 40 by 400 in HE.

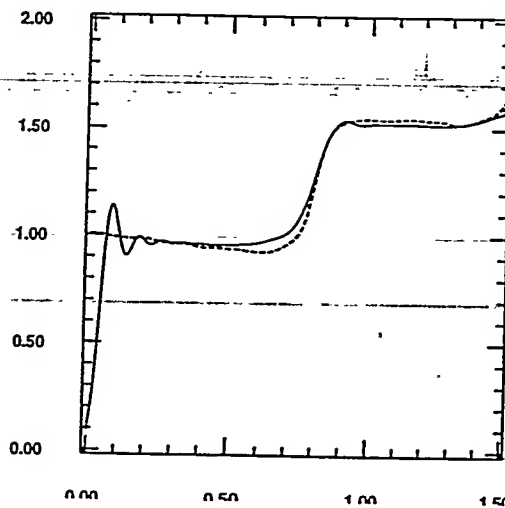


Fig. 5. Comparison of ten elements/mm to experimental result (spall suppressed).

As the number of elements increases, we see a decrease in the period and magnitude of the sinusoidal wave associated with the initial rise. Ultimately, we find that very fine zoning and an aspect ratio of about 1 in the plate is required to match the experimental velocity wave profile. The calculated result with 10 elements/mm in the plate (20x1000) and 5 elements/mm in the explosive (40x500) is compared to the experimental result in Figure 5. We conclude that this is the minimum acceptable zone density for studying shock wave effects in a shaped charge or efp liner. This is consistent with thin walled cylinder test and analysis results [13].

SHOCK AND DETONATION WAVE PROFILE

A description of the calculated 10 element/mm shock wave profile in the copper and the detonation wave profile in the HE is shown in Figure 6. The detonation wave in the HE is moving upward at about 8.8 mm/ μ sec while the shock in the copper is moving to the left through the plate at about 4.4 mm/ μ sec. Thus, the wave front is moving through the copper at about a 63 degree angle. The dark fringes indicate a pressure greater than 0.300 Mbar while the lightest fringe color is for a pressure of less than 0 (tensile pressure). This figure shows three of the many HE driven shocks that are reverberating through the copper liner during the collapse process. Each of these reverberations corresponds to a jump in the free surface velocity that is measured by the FP. Several phenomena can be observed from this simulation:

1) These finely resolved simulations show a peak tensile pressure greater than 0.030 Mbar in the region between the first and second shock reverberations.

2) The tensile pressure region between the first and second reverberations moves as much as 75 percent of the way back toward the explosive. With this large of an area and magnitude of tensile pressure we wonder if the plate spalls, fails, or is damaged in some way.

3) The reverberations in the plate continue long after the detonation wave has passed. These reverberations are the cause of pressure oscillations observed in the collapse region by many others.

4) Aspect-ratio 1 elements are required to accurately resolve the shock front as it propagates through the plate.

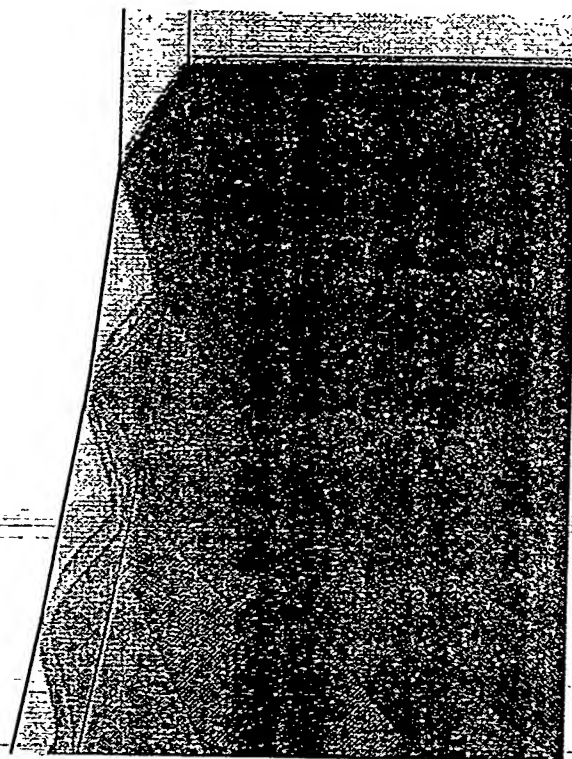


Fig. 6. Description of shock wave in the liner and detonation wave in HE at 6 μ sec.

Using this finely resolved mesh model that is required to match the experimental results, we now look again at copper material failure as well as at the modeling effects of strength and artificial viscosity.

FAILURE MODEL EFFECTS

A simple pmin model was used to simulate the effect of failure in the copper plate. Although using a pmin model to treat failure is inadequate, it is very simple method for studying material failure and it is easy to observe the cause and effect of "damage". The effect of using pmin values of -0.012, -0.025, and -0.050 Mbar are compared to the experimental result in Figure 7. Several phenomena can be observed from these simulations:

1) The pmin of -0.050 Mbar (lowest solid line) most closely matches the experimental result.

2) The -0.012 and -0.025 Mbar p_{min} models seem unreasonable because of the long time delay for the arrival of the second shock reverberation through the plate. In these simulations, the free surface side of the plate fails and pulls away from the remaining plate material. The time delay required to close the gap during the second shock reverberation is too long.

3) The effect of simulating material failure is no longer observed after the rise in plate velocity for the second shock reverberation and beyond. From this point on (beyond 1 μ sec), it does not matter what p_{min} value is used because all of the simulations match each other.

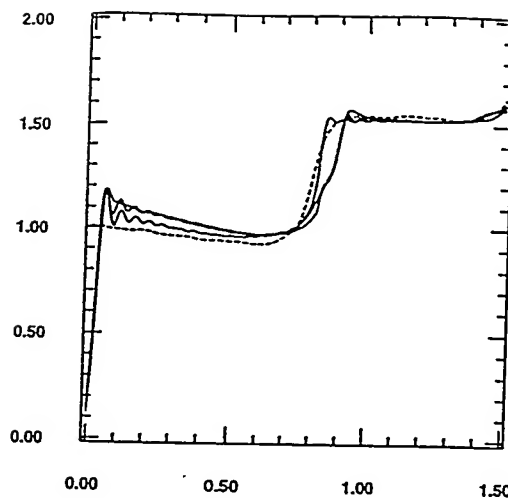


Fig. 7 Effect of using p_{min} values of -0.012, -0.025, -0.050 Mbar

Our conclusion is that some material damage occurs during the first shock reverberation. Annealed copper cannot support a tensile pressure greater than 0.030 Mbar. However, there is not sufficient time for a "spall" to develop and the second shock recompresses the microporosity created from the rarefaction of the first shock. The material damage observed here is not like "flyer driven spall" where a single shock pulse causes a single rarefaction. We observe multiple shock pulses resulting in increasing plate velocity such that even if material failed at the free surface, it could not separate and pull away from the remaining plate material.

STRENGTH MODEL EFFECTS

The simulations showing the effects of different strength models were conducted with the fine mesh defined in the mesh density study: 10 elements/mm in the plate (20x1000) and 5 elements/mm in the explosive (40x500). The flow stress for the copper was modeled using the rate-independent version of the Steinberg-Guinan viscoplastic model [9]. The Johnson-Cook [10] and Zerilli-Armstrong [11] copper deviatoric models were also studied using parameter values defined in a previous study [12]. These results, presented in Figure 8, show there is basically no difference in the calculated plate velocity for the three material strength models.

ARTIFICIAL VISCOSITY MODEL EFFECTS

The simulations showing the effects of artificial viscosity models and values were also conducted with the mesh defined in the mesh density study. The objective of using artificial viscosity is to spread the discontinuous shock over a small number of elements while damping the oscillations (observed behind the shock front) that are caused by the numerical method itself [14]. Simulations using the "standard" DYNA2D model with the default value and with twice the default and half the default values are compared to the experimental results in Figure 9. The Richards-Wilkins viscosity model [14,15] was also evaluated and it produced the same

basic results. The twice default Q values show a lower overshoot on the first rise and a lower magnitude oscillation (increased damping). All models match each other after 200 nsec.

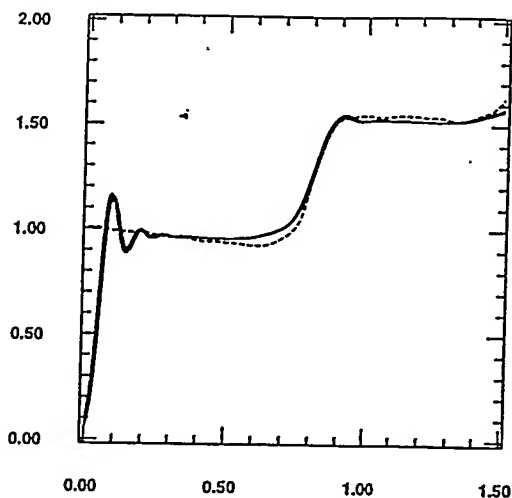


Fig. 8. Comparison of the SG, JC, & ZA material strength models to experiment.

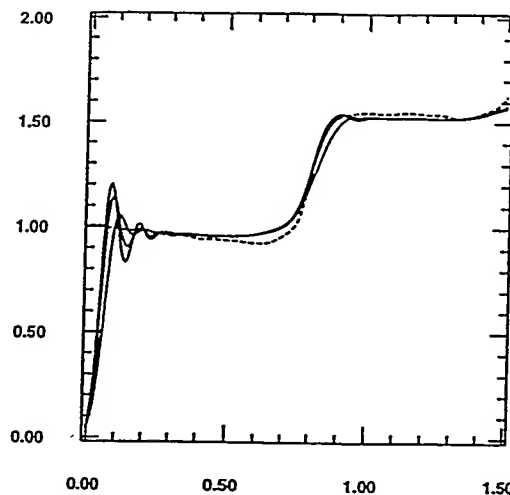


Fig. 9. Comparison of artificial viscosity effects: default, double and half default.

CONCLUSIONS

A minimum of ten elements per millimeter through the plate thickness as well as along the plate (in the direction of the detonation wave propagation) is required to match the experimental plate velocity wave profile. Fewer elements may be used to match total momentum transfer, but not wave profile. The aspect ratio of the elements should be about one in order to correctly model the shock going through the plate at 4.4 mm/ μ sec which is driven by the explosive detonation moving up the plate at 8.8 mm/ μ sec. We have found that the strength model has no effect on the calculated plate velocity while the artificial viscosity models and values have a small effect in the first push and no effect beyond 200-nsec.

We conclude that some material damage occurs as a result of the rarefaction from the first shock through the plate. However, there is not sufficient time for a "spall" to develop before the arrival of the second shock reverberation. The plate material stays intact, albeit damaged. The effect of simulating material failure using small and large values of p_{min} is no longer observed beyond the rise in plate velocity for the second shock reverberation. From this point on (beyond 1 μ sec), all of the simulations match each other. Thus, we conclude that the plate or liner is damaged, or failed, but remains intact.

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